

TIME-DEPENDENT SEISMIC TOMOGRAPHY OF THE COSO GEOTHERMAL AREA, 1996-2004

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ABSTRACT

Local-earthquake tomographic images were calculated for each of the years 1996 - 2004 using arrival times from the U.S. Navy's permanent seismometer network at the Coso geothermal area, California. The results show irregular strengthening with time of the wave-speed ratio V_P/V_S at shallow depths. These changes result predominately from progressive relative increase in V_S with respect to V_P , and could result from processes associated with geothermal operations such as decrease in fluid pressure and the drying of argillaceous minerals such as illite.

INTRODUCTION

Studies at several geothermal areas show that (1) geothermal reservoirs often exhibit strong anomalies in the ratio, V_P/V_S , of the seismic-wave speeds (Julian et al., 1996), and (2) economic exploitation can cause measurable changes in seismic wave speeds, which may provide valuable information for monitoring reservoir processes critical for sustained production (Foulger et al., 1997; Gunasekera et al., 2003). We investigated the possibility of such changes during the period from 1996 through 2004 at the seismically active Coso geothermal area. We used data from the U.S. Navy's permanent 18-station seismometer network (Figure 1). This network provides high-quality three-component digital microearthquake (MEQ) data that are well suited to such an investigation.

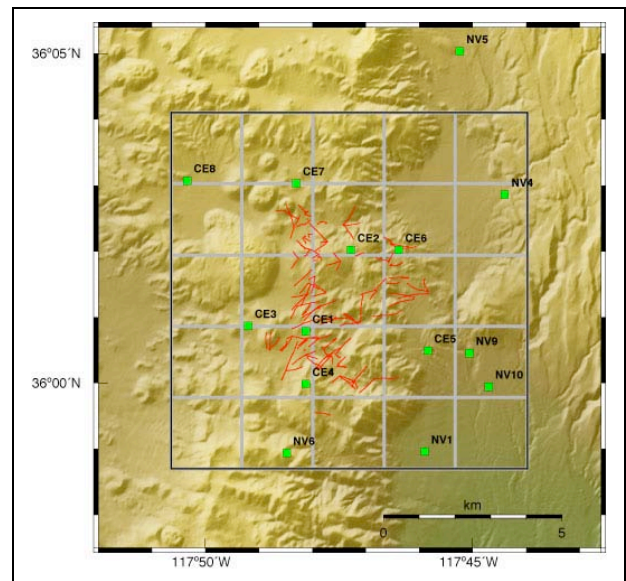


Figure 1: Map of the Coso geothermal area, showing the surface projection of the grid upon which the seismic wave-speeds are defined. Green squares: seismometers of U.S. Navy's permanent network. Red lines: surface traces of well bores.

DATA SELECTION

We winnowed the large data set of arrival times in the Navy MEQ catalog to reduce redundancy and eliminate low-quality data, ranking events in terms of the number and geographic distribution of seismic readings available and the goodness-of-fit to the arrival times for each event. We kept the best 10

events in each 1x1-km block. The winnowed data set comprises 4,811 earthquakes and 79,822 P - and S -wave arrival times. Figure 2 shows the locations of the winnowed events for two typical years.

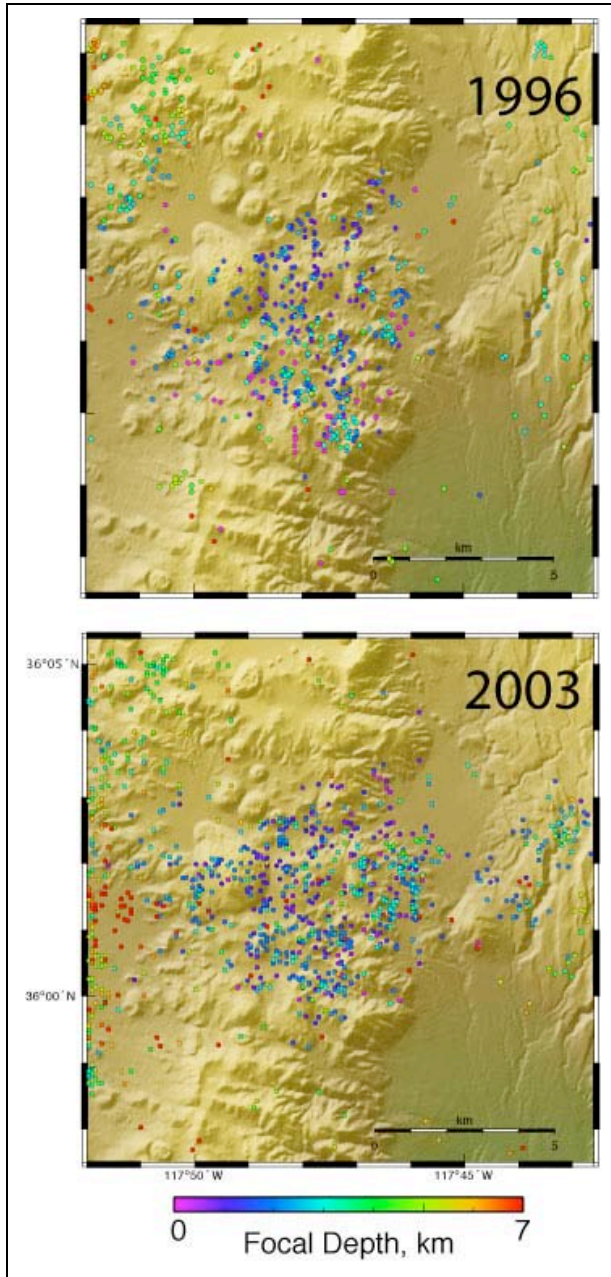


Figure 2: Locations of winnowed earthquakes for the years 1996 and 2000, illustrating typical year-to-year variations.

TOMOGRAPHIC INVERSION METHOD

First, we inverted the entire winnowed data set using the computer program *velest* (Kissling et al., 1994) to estimate the average one-dimensional seismic velocity structure (wave speeds vs. depth). Second, we used this structure as a starting model and, using the computer program *simul2000A* (Evans et al.,

1994; Thurber, 1993) inverted the entire winnowed data set to obtain an average three-dimensional model for the entire time period. Finally, we used *simul2000A* to invert the data for each of the years 1996 – 2004 independently. We repeated this three-dimensional inversion procedure twice for each year: first with a 2-km horizontal grid spacing and then with a 1-km horizontal grid. In all cases the vertical grid spacing was 1 km.

RESULTS

Figure 3 summarizes the results for the independent year-by-year inversions. It shows, for each of nine separate years, maps of the distributions of V_P , V_S , and the V_P/V_S ratio at four levels between 1 km above sea level (near the surface) and 3 km below sea level. The main results may be summarized:

1. Compared with the crustal model currently used by the U.S. Navy for routine earthquake location, the average one-dimensional crustal structure we obtained has somewhat lower wave speeds at shallow depth and significantly higher ones at greater depth. Use of a model with higher wave speeds in general will result in shallower estimated earthquake hypocentral depths.
2. The area is characterized, on average, by relatively high V_P/V_S in the upper ~ 4 km, beneath which the value of this ratio decreases. This change is most likely caused by petrological variations.
3. Low V_P and V_S wave speeds are associated with sediments in the Coso Wash and Coso Basin. A V_P/V_S low occupies the northern and eastern part of the geothermal field near the surface (~ 1 km above sea level), and the northern and southern parts of the field near sea level.
4. Independent inversions for each of the years 1996 - 2004 separately show, for the 2-km horizontal grid spacing, an irregular strengthening with time of the negative V_P/V_S anomalies between the surface and sea level. This progressive reduction in V_P/V_S results predominately from a increase in V_S with respect to V_P . Such a change is expected to result from effects of geothermal operations such as decreasing fluid pressure and the drying of argillaceous minerals such as illite.
5. Inverting the data with a 1-km horizontal grid spacing produced noisier results without significantly reducing data variance. From this we conclude that the density of seismic stations in the area as a whole is insufficient to improve horizontal spatial structural resolution beyond about 2 km.

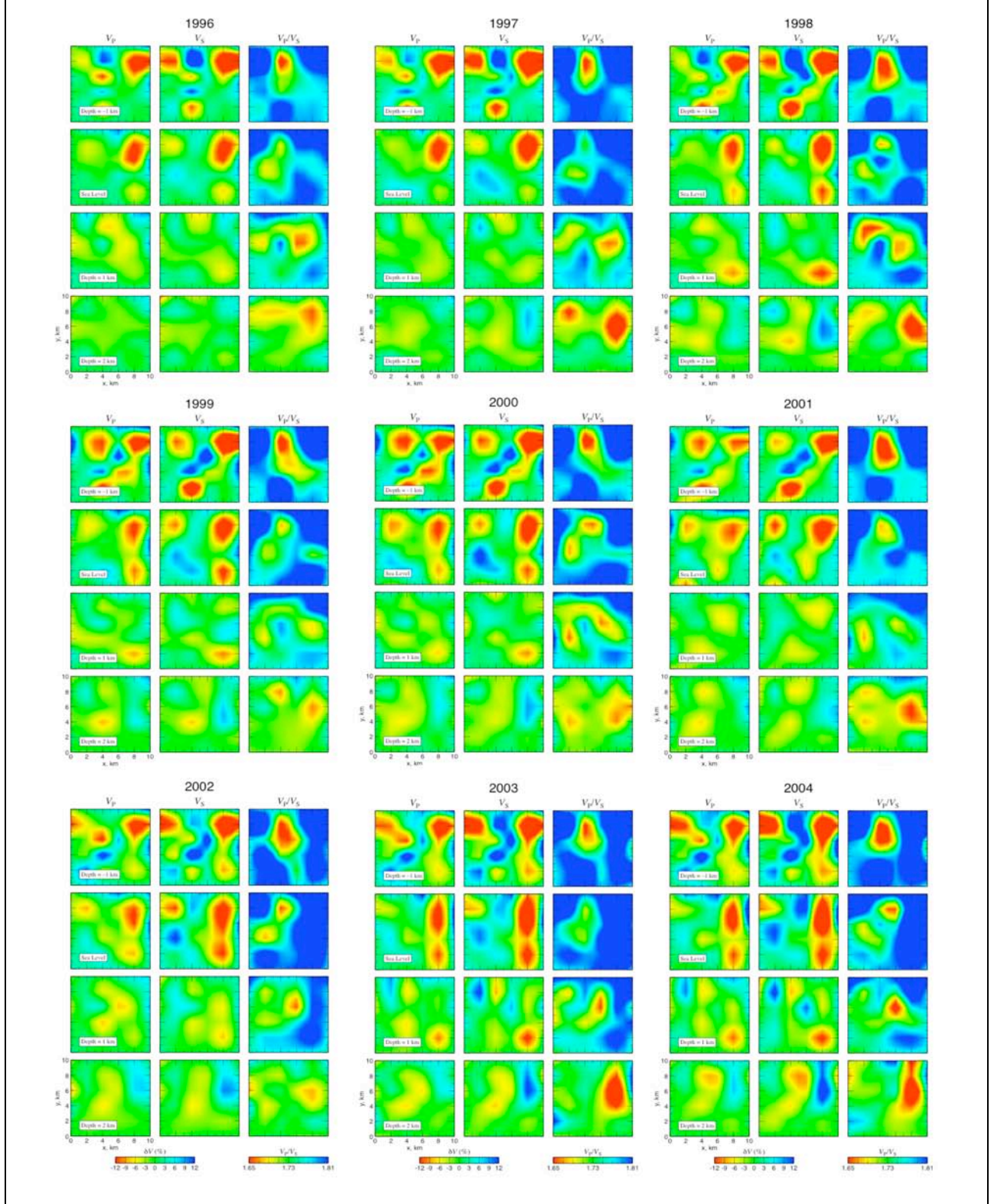


Figure 3: Maps of V_p , V_s , and the V_p/V_s ratio at different depths for the years 1996-2004. The area shown is that of the grid shown in Figure 1.

CONCLUSIONS

The average seismic wave speeds throughout the shallow crust beneath the Coso geothermal area are somewhat higher than those currently used by the U.S. Navy for routine locations, suggesting that earthquake hypocentral depths may be slightly underestimated in the U.S. Navy catalog. Negative V_p/V_s anomalies in the upper ~ 2 km beneath the production zone strengthened irregularly in the period 1996 - 2004, probably as a result of production activities. The present network is not sufficient to image structure tomographically on a scale smaller than ~ 2 km horizontally. A finer scale of imaging might be achievable locally where a dense, portable network has recently been deployed to monitor EGS experiments in the East Flank area.

REFERENCES

- Evans, J.R., Eberhart-Phillips, D. and Thurber, C.H., 1994. User's manual for SIMULPS12 for imaging V_p and V_p/V_s , a derivative of the Thurber tomographic inversion SIMUL3 for local earthquakes and explosions, USGS.
- Foulger, G.R., Grant, C.C., Ross, A. and Julian, B.R., 1997. Industrially induced changes in Earth structure at The Geysers geothermal area, California. *GRL*, 24(2): 135-137.
- Gunasekera, R.C., Foulger, G.R. and Julian, B.R., 2003. Reservoir depletion at The Geysers geothermal area, California, shown by four-dimensional seismic tomography. *JGR*, 108(B3): 2134, doi:10.1029/2001JB000638.
- Julian, B.R., Ross, A., Foulger, G.R. and Evans, J.R., 1996. Three-dimensional seismic image of a geothermal reservoir: The Geysers, California. *GRL*, 23(6): 685-688.
- Kissling, E., Ellsworth, W.L., Eberhart-Phillips, D. and Kradolfer, U., 1994. Initial reference models in local earthquake tomography. *JGR*, 99: 19635-19646.
- Thurber, C., 1993. Local earthquake tomography: velocities and V_p/V_s - Theory. In: H.M. Iyer and K. Hirahara (Editors), *Seismic Tomography: Theory and Practice*. Chapman and Hall.